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Dredging as Remediation for White Phosphorus Contamination at Eagle River Flats, Alaska

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Abstract: The Eagle River Flats impact area is a Ft. Richardson Superfund site. It is a salt marsh that is contaminated with white phosphorus (WP), and remediation of sediments in permanently ponded areas may require dredging. A remotely piloted dredging system was designed, constructed, and deployed at the Flats as part of the overall site remediation feasibility study. Experience gained over two years of engineering study and contract operation indicates that, although feasible and effective, this alternative is slow, difficult, and very expensive.

Cover: Start of dredging operations off Clunie Point, Eagle River Flats, Alaska, in June 1995. The operator cab is in the center of the gravel pad; the dredge is to the right.

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PREFACE

This report was prepared by Michael R. Walsh, Mechanical Engineer, Engineering Resources Branch, Applied Sciences and Technology Directorate, U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, and Charles M. Collins, Research Physical Scientist, Geological Sciences Division, Research and Engineering Directorate, CRREL, Fairbanks, Alaska.

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Technical review of this manuscript was provided by Karen Henry and Leonard Zabilansky of CRREL. Valuable assistance was provided by Dennis Lambert, Troy Arnold, Anthony Wood, and Ronald Poulson of CRREL who worked on the modification, deployment, and operation of the dredge system; Donald Garfield, Edward Chamberlain, and Karen Henry of CRREL who supported this project with their technical expertise; Edward Sorenson and Tom Lubec of the Alaska District for their assistance with the retention basin; Timothy Welp of the Waterways Experiment Station Basin for his assistance in troubleshooting the dredge; William Smith and Laurie Angell of the USARAK Directorate of Public Works (DPW) Environmental Division for their logistical and administrative support in Alaska; and Travis Barber, George Boice, Michael Hamilton, and John McKiernan of the USARAK DPW Roads and Grounds Division for their assistance with construction and logistics.

The authors dedicate this report to the memory of CWO Michael J. Arline, helicopter pilot for the Alaska Army National Guard. Mike was with the project from its inception, and his skills and stories will be greatly missed.

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Dredging as Remediation for White Phosphorus Contamination at Eagle River Flats, Alaska

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INTRODUCTION

Eagle River Flats (ERF) is an estuarine salt marsh located on Ft. Richardson near Anchorage, Alaska (Fig. 1). For fifty years, it has been used as an impact area by both the Army and Air Force. During the 1980s, thousands of dead and dying waterfowl were found in this area during spring and fall migrations. For five years, various state and federal agencies tried without success to unravel the mystery of this high mortality. Finally, in the spring of 1990, a team of researchers from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), working in conjunction with the Ft. Richardson Directorate of Public Works, Environmental Division (DPW-EV), discovered the cause of these massive die-offs: poisoning due to the ingestion of white phosphorus (WP) particles in the sediments of ponded areas (Racine et al. 1992).

With this discovery, firing of white phosphorus into the Eagle River Flats impact area (the Flats) was halted, but the highly persistent residual particles of WP continued to take their toll on the waterfowl population. Investigations into the behavior and extent of the contaminant were conducted, followed by a parallel investigation into various methods of remediating the most hazardous areas.

Dredging is one of several options evaluated during the remediation feasibility study conducted at the Flats since 1994.

Figure 1. Eagle River Flats, Alaska.

BACKGROUND

White phosphorus is used by the Army as a targeting and obscurant round. Because white phosphorus is extremely volatile in air (pyrophoric), the common assumption is that, upon detonation, all the material in a round is consumed. However, evidence of the persistence of white phosphorus in the environment has previously been documented, most notably in Placentia Bay, Newfoundland, in 1968 (Idler 1969). The U.S. military has also had experience with WP contamination of the environment (Sullivan et al. 1979). Although information is available as to the toxicity and persistence of white phosphorus, it was not widely known or perceived to be a problem at the time the die-offs were first being investigated. An early study at the Flats in fact dismissed WP as a causal agent (ESE 1990).

With the cause of the mortality at the Flats identified, investigations were initiated to determine the biological and physical extent of the white phosphorus contamination (Racine et al. 1992, 1993). Remediation feasibility studies at the Flats were initiated in 1994. Two parallel strategies were pursued: removal and in-situ treatment. The in-situ work is generally less intrusive than removal. It ranges from enhancement of natural attenuation and pumping or draining of contiguous ponded areas to covering contaminated areas with geotextiles or a bentonite–ballast mixture. Each methodology is best applied to specific areas. Large, deep, contiguously ponded areas were targeted for dredging.

DREDGE DESIGN

An augerhead-type hydraulic dredge (Fig. 2) was leased locally and modified for the dredging operations (Walsh et al. 1996). An augerhead dredge was specified due to the nature of the contaminant. White phosphorus is easily resuspended in water and settles slower than the sediments found at the Flats due to its lower specific gravity. The enclosed augerhead contains the sediment during the dredging process, thereby reducing the recontamination of the dredged area. The dredge traverse system was anchored using 1-m^3 (1800-kg) concrete deadmen placed by helicopter, supplemented by screw anchors placed in areas cleared of ordnance (Fig. 3). The use of spuds and lateral cables was considered but rejected on the basis of the danger involved in setting the spuds in the sediment of the Flats as well as the difficulties involved in excluding ordnance from the basket dredge head. It is also more difficult to operate this type of system remotely.

Due to the possibility of encountering unexploded ordnance and debris in the Flats while dredging, a method of excluding these items from the pump was designed and installed on the dredgehead inlet. Several options were tried initially, including screening the inlet, separating ordnance in a flow expander box, and adding a grate to the expander box. Although all these alternatives were effective in excluding ordnance from the pump, they eventually failed due to the presence of heavy vegetation and woody debris, which either clogged the screens or passed

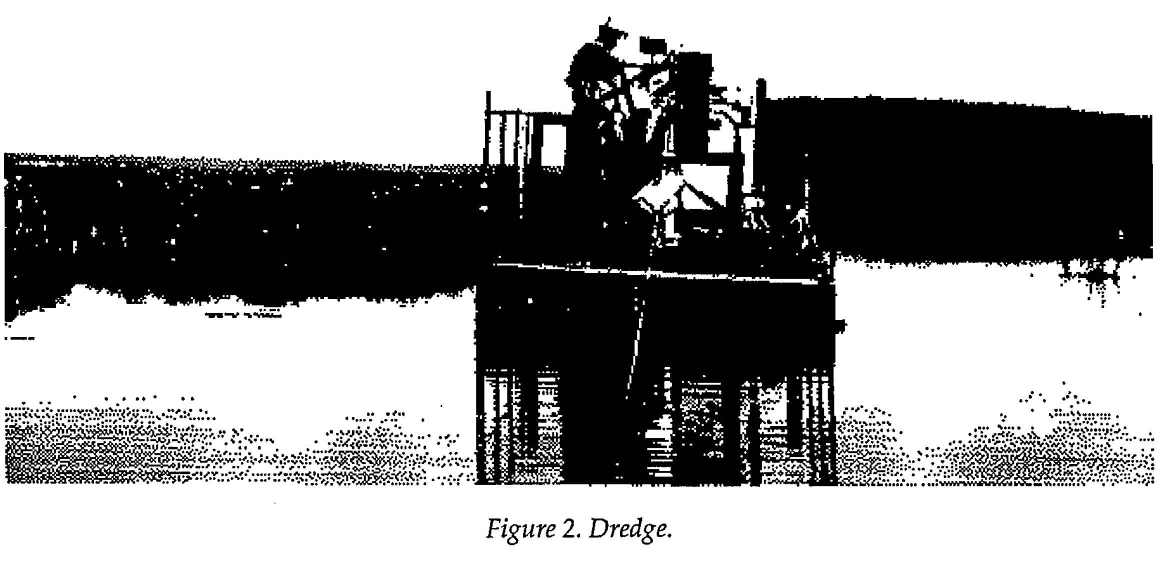


Figure 2. Dredge.

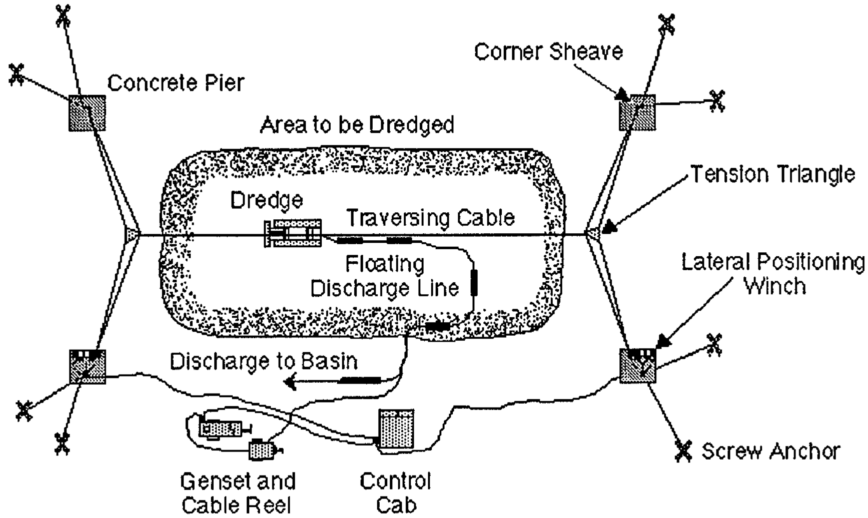


Figure 3. Dredging layout.

through to the pump, lodging in the pump eye. Analysis of pump behavior and assessment of the dredging environment led to a solution. This is a cutter and grate system with auxiliary tines on the auger, which excludes items with a dimension larger than 13 mm (Fig. 4). Vegetation is sheared by the cutter as it passes the top of the grates. This system allowed almost continuous dredging in the very difficult conditions encountered at the Flats.

Spoils are pumped from the dredge to shore through 20-cm-diam. × 76-m flexible rubber hose sections. On shore, the hose transitions to 25-cm-diam. × 12.2-m polyethylene pipe sections for the 335-m trip to a retention basin. The spoils are then held in the basin until the larger solids (> 0.1 mm diam.) settle out, whereupon the supernatant is decanted over a weir and back into the Flats via an outflow pipe. The sediment retention basin was constructed on the Explosive Ordnance Disposal (EOD) pad with compacted native and imported gravel. Special precautions had to be taken to ensure that water from the spoils pumped by the dredge would not percolate through the pad and mobilize contaminants that may lie beneath it. Working with the Corps of Engineers Alaska District, a 0.8-ha retention basin structure capable of containing 1.2 ha-m of spoils was designed and built. Extensive testing of the pad and the basin were conducted both at CRREL and on site to

Figure 4. Cutter and grate system for dredge intake.

determine the optimal method of achieving minimal percolation rates into the pad. With a 15-cm layer of compacted peaty silt lining the basin, percolation rates were low enough ($<10^{-5}$ cm/s) to be acceptable for use. The basin was instrumented to monitor water level, sediment and air temperature, and sediment moisture, parameters critical to the remediation process for WP.

INITIAL DEPLOYMENTS

Initial deployment of the dredge took place in October of 1994 (Walsh et al. 1996). Due to the lateness of the season and delays caused by improperly running equipment, very little dredging was accomplished. Enough spoils were pumped for only two composite samples, one of which was heavily contaminated. However, results demonstrated that an operable dredge system will effectively remove contaminants from the environment.

Early in the 1995 dredging season, a number of improvements were made to the equipment, but problems continued to plague the operation. Initial dredging operations were quite discouraging, showing little improvement over the previous season. Output from the various dredge sensors was still unusable, reading below known maximum system values at full operating conditions, and the pump was not operating correctly. Top speed was attained at about 50% of hydraulic throttle, and spoils flows could not be maintained. In addition, the 25-cm-diam. flexible sections in the spoils line continued to blow fittings. Consultations with the equipment manufacturer did not result in a solution, and discussions with the pump manufacturer and an engineer at the Waterways Engineering Station in Vicksburg indicated that a second look at the pump was warranted.

After two unsuccessful attempts at using the system as configured, the decision was made to start from scratch and troubleshoot every suspect component in the system. The following is a list of problems uncovered and actions carried out to resolve them.

Flexible hose sections

Due to poor construction, end connectors on the 25-cm-diam. hose sections failed on a regular basis. All the flexible hose sections in the spoils line were removed and replaced with short sections of rigid PVC pipe. After one section of PVC pipe blew an end fitting, the number of screws holding the fittings to the pipe ends was doubled from two to four. No further problems were encountered.

Sensors

Closer examination of the dredge function feedback sensors (intake suction, pump output pressure, system hydraulic oil pressure, and centrifugal pump hydraulic oil pressure) indicated that the output signal range was from 1 to 6 VDC, not the 0–5 VDC specified in the contract. This resulted in miscalibration and the clipping of the higher signal output (5–6 VDC). In addition, the sensors were wired to the wrong inputs on the video panel meter that transforms the sensor signals into output data for transmission over the video system. These were rewired to the correct inputs. A voltage reduction circuit using precision resistors was designed at CRREL and installed between the sensor output leads and the video panel meter (Fig. 5). This circuit attenuates the signal 20%, resulting in an input signal of 0.8 to 4.8 VDC to the panel meter. Voltages now corresponded to the range of the panel meter, 0–5 VDC. The panel meter was reprogrammed and pumping tests rerun to obtain data for pump evaluation.

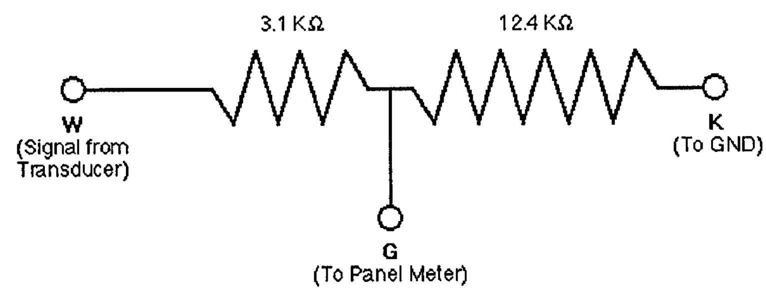


Figure 5. Sensor voltage divider (typ. each sensor).

Pump

With the sensors wired correctly and recali-

Table 1. Pump performance test.

Control setting (%)	*Outlet pressure Sensor (kPa)*	*Outlet pressure Gauge* (kPa)*	*Shaft speed (rpm)*	*Hydraulic drive (MPa)*	*Current draw (amps)*	*Output flow (visual)*
100	103	117	1257	23	50	Full
95	103	117	—	23	—	Full
90	103	117	1269	23	—	Full
85	103	117	—	23	—	Full
80	103	117	1270	23	50	Full
75	103	117	—	23	—	Full
70	103	117	1275	23	—	Full
65	103	117	—	23	—	Full
60	103	117	1280	23	50	Full
55	103	117	—	23	—	Full
50	103	117	1282	23	—	Full
45	103	117	—	23	—	Full
40	90	103	1116	18	25	≈3/4
35	76	90	—	13	—	≈1/2
30	62	76	806	10	—	≈3/8
25	55	70	—	6.6	—	≈1/4
20	41	55	492	3.4	≈7	0
15	48	48	—	5	—	0
10	—	—	135	—	—	0
5	—	—	—	—	—	0
0	—	—	0	—	≈5	0

* 1.4 MPa gauge

brated, a series of tests pumping clean water were conducted. In these tests, generator current; pump RPM; pump inlet, outlet, and hydraulic pressures; pump throttle setting; and outflow volume were monitored. Results are shown in Table 1.

Using this data as a baseline, an analysis of the pump parameter options was conducted (App. A). In these analyses, various impeller diameters were examined at specific speeds, using standard friction factors for the system components. Power requirements for the 356-mm impeller were checked to ensure compatibility with system capability (Table 2). A top speed of around 1500 rpm was chosen to allow sufficient power to the other components on the dredge system.

With the final pump configuration determined from analytical methods, pumping tests were re-

Table 2. Slurry pump power requirements.

Impeller speed (rpm)	*Pressure (MPa)*	*Flow (L/s)*	*Power (kW)*
1280	24.1	1.4	32.9
1280	31.0	1.4	42.3
1500	24.1	1.6	38.6
1800	24.1	1.9	46.3
1800	31.0	1.9	59.5

Table 3. Final pump performance test results.

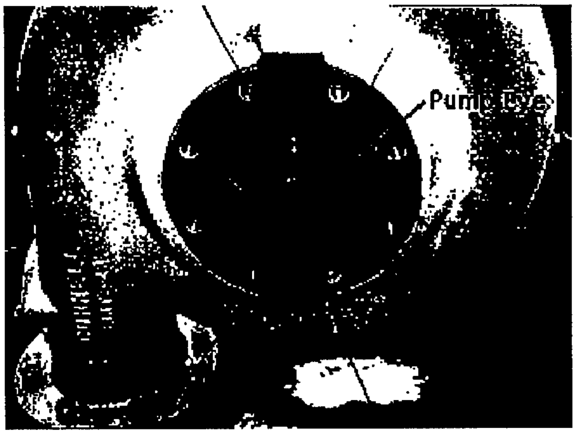
Control setting (%)	*Slurry pump Outlet (kPa)*	*Slurry pump Hyd. (MPa)*	*Outlet flow (visual)*
100	108.9	33	Full pipe
95	108.9	33	Full pipe
90	108.9	33	Full pipe
85	108.9	33	Full pipe
80	108.9	33	Full pipe
75	108.9	33	Full pipe
70	108.9	33	Full pipe
65	104.8	31	Full pipe
60	95.1	27	Near full pipe
55	85.5	23	Near full pipe
50	75.8	20	Near full pipe
45	64.1	16	≈7/8 pipe
40	54.5	12	≈3/4 pipe
35	47.6	10	≈5/8 pipe
30	42.7	6.2	1/3 to 1/2 pipe
25	37.9	4.8	Trickle

run to determine if the these results were valid. Slurry pump outlet pressure was monitored to determine system capability, as this is a good indicator of output capability. The results of these tests are found in Tables 3 and A2.

Grates

Although the dredge system is designed to process vegetation, the presence of boardwalk and other woody debris was problematic for the pump. Chunks of wood became lodged in the eye of the pump during dredging operations, and the blockage quickly accumulated other debris in a process called "beaver-damming" (Fig. 6). Evidence of this phenomenon first surfaced during pumping tests, with cyclic surging, the period of which was related to impeller speed. The surging was caused by cavitation due to inlet starvation and the backflow of water into the pump. When pump blockage was suspected, the dredge was pulled from the water and the pump eye examined. It was found to be clogged with debris. The instigators in all occurrences were waterlogged sections of boardwalk approximately 70 mm × 20 mm × 150 to 200 mm long. Because the wood was of near-neutral buoyancy, it did not drop out in the expansion (boom) box located ahead of the pump. We also found that aluminum objects did not always drop out.

Although the boom box was effective in keeping out the heavier steel debris, it was not functioning when confronted with lighter materials. A coarse screen system was installed in the boom box, but that quickly plugged, crippling the



a. Debris in pump eye.

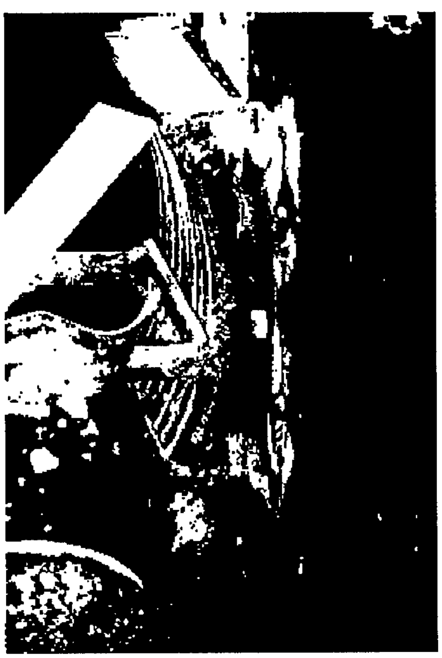
b. Extracted debris. Note aluminum illumination round section.

Figure 6. Slurry pump eye clogging.

dredge within a matter of minutes. A new approach was needed that would exclude debris from the pump but not become clogged with the ubiquitous vegetation.

The solution is a cutter and grate system for the auger head (Fig. 7). The vertical grates are attached to the front of the dredge head where the intake is located. A cutter bar, attached to the center of the auger, keeps the grates clear of vegetation by sweeping debris up the grates and cutting it at the top. A tapered transition section behind the grates smooths the flow of water from a rectangular cross-sectional opening to a 15-cm-diam. hose adapter. Stiff tines are attached to the auger flites to augment maceration of vegetation prior to ingestion.

The original system was designed to function as a bolt-on assembly for ease of modification



a. Side view of grates with cutter.

b. Debris extracted from gates, with pen for size comparison

Figure 7. Test cutter and grate system for dredge augerhead intake.

during testing. Operational usage of the system indicated that extended run-time was possible with the grates installed. However, some plugging of the grates was experienced. For the most part, the debris was confined to the upper and lower 5 cm of the grates. The material lodging in the grates consisted of small chunks of wood (boardwalk), hard vegetative nodules, and root masses. Some modification of the grates was done to reduce entrapment, but the cause of the plugging was the deflection of the grates by material slightly larger than the grate openings.

During the interval between the July and September deployments in 1995, an improved system was designed and fabricated. The grates were stiffened by using thicker stock for fabrication, 9.5 mm rather than 4.75 mm. The grates were machined in a T shape to allow slightly oversized debris to pass through without jamming. An improved transition box behind the intake allows backflushing and manual cleaning of the rear of the grates. Finally, the grates were designed to fit flush with the front of the auger head shroud (Fig. 8).

Auger drive motor

The stiff tines and cutter of the cutter/grate system added to the torsional resistance of the auger. A new hydraulic augerhead motor with twice the torque and half the speed of the original was installed. In the process, the hydraulic hoses were replaced, as they had been abrasively worn. During dredging operations, the protruding drive motor is forced through the undredged material to the side of the dredgehead. This causes wear on the component as well as resistance to forward motion. The drive motor needed to be located behind the shroud, and the auger driven with a chain.

With these changes made to the system, actual production dredging commenced in mid-September of 1995. Progress was slow but consistent, with the processing of vegetation continuing to be problematic. Difficulties with the winch traverse system persisted, but solutions were formulated and these difficulties were circumvented on a temporary basis. A series of unrelated events closed down operations at the Flats, and on 24 September, dredge operations were halted for the season.

a. Cutter and grates. Note vertical stiff tine.

b. Top view of transition box showing manual cleanout.

Figure 8. Mk. II cutter/grate system.

RESULTS OF 1995 WORK

During dredging operations in 1995, a total of 137 sediment samples, 23 water samples, four total suspended solids (TSS) samples, and one spoils line solids content and grain size analysis sample were taken and analyzed. Each of these data categories is discussed below, as well as an analysis of the results, an estimate of material removed, and a cost estimate for removal.

Sample analysis for white phosphorus

The large number of sediment and water samples should give a reasonable indication of the contamination of each material. Table 4 is a summary of the data in Appendix B on the sample analyses done for the dredging project in 1995. As can be seen from the table, about 19% of the sediment samples were hits. This is consistent with the results of random sampling done by other researchers at the Flats. The range of concentrations for the analyzed sediment positive readings or hits is low, indicative of nonparticle hits. This may be due to the sampling technique. The sample port is located halfway to the top of the pipe and is perpendicular to the flow of the spoils, thus larger grains and particles may not be drawn through the port. Grinding and mixing of the particles over the 720-m length of the spoils line will also have an effect on particle size. The water hit may be attributable to sediments in the basin stirred up during lowering of the weir in the retention basin (samples were collected from the outfall pipe). It is a single hit that is not of great magnitude and too small to be dangerous to waterfowl.

Table 4. Results of dredge sample chemical analyses (1995).

	No. of samples	*P_4 hits*	*Hits (%)*	*Range (µg/kg)*	*Average (µg/kg)*
Sediment (spoils)	137	26	19	0.22–66.00	6.16
Water (supernatant)	23	1	4	—	4
Total	160	27	17	—	—

Total suspended solids

Due to the slow settling of the solids suspended in the water column, supernatant decanted over the weir and out to the settlement basin was not of the quality originally anticipated. For this reason, four samples were taken from the basin outlet pipe for TSS analysis. Table 5 shows the results of these analyses. For comparison, normal TSS at ERF is 10 to 20 mg/L, and TSS during flooding events is 1000 to 3000 mg/L* (Bouwkamp 1995).

Table 5. Total suspended solids analysis (1995).

Sample	*TSS (mg/L)*
15 September 1995	215
16 September 1995	1595
19 September 1995	611
20 September 1995	850

From these data, it is clear that the supernatant exiting into Area C is not degrading the water quality of the Flats. It should also be noted that the area in which the Basin is draining is heavily vegetated, and thus the solids should drop out more efficiently due to slower-moving water. Most important, any trace WP in the stream should quickly sorb to the organic matter in the area.

Grain size analyses

Grain size analyses were done on two samples. The first was a spoils sample taken directly from the sampling port of the spoils line. The second was taken from a TSS sample of the basin outlet runoff. Results of the analysis of the spoils line sample are shown in Table 6. The spoils sample was taken from the spoils line on 27 July 1995. The sample volume was 500 mL, with a weight of solids of 18.2 g. The percent solids is 3.87%, and salinity was 1.1 ppt. Grain size from this sample is also graphed in Figure 9.

Table 6. Grain size analysis: Spoils sample.

Diameter (mm)	*Percent finer*
0.0327	96.3
0.0208	90.9
0.0122	82.6
0.0087	71.8
0.0061	60.9
0.0029	44.3
0.0013	30

The one TSS sample that was examined for grain size was checked only against the no. 200 sieve (0.075-mm particle diameter). Only 1% of the sample was retained. Other sieve sizes were not checked due to the small volume of the sample and the small particle sizes. We were most concerned with particles greater than 0.1 mm diameter, as those are most lethal to some waterfowl at ERF.†

Estimated contaminant removal

The volume of material removed from ERF is difficult to estimate due to the disturbance of unexploded ordnance (UXOs) in the dredged area.

* Conversation related to TSS measurements done on dredging samples, S. Bigl, USA CRREL, 1995.

† Personal communication on WP contamination and lethal dose size, based on unit weight, M.E. Walsh, USA CRREL, 1994.

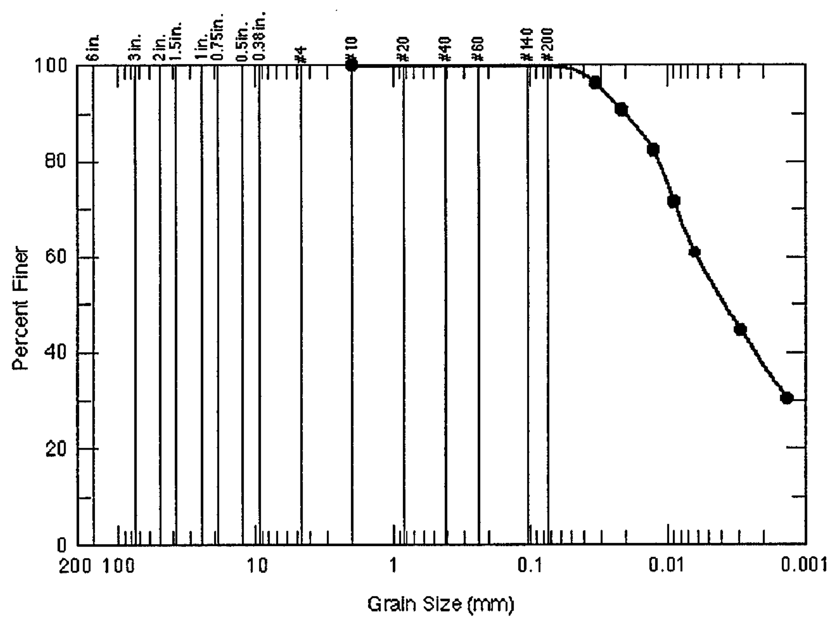


Figure 9. Grain size analysis for spoils sample (1995).

A rough estimate can be obtained from observations of the quantity of sediment in the settlement basin. At the cessation of dredging activities in late September, the quantity of material in the Basin would fill about one third of the area to the 60-cm level. This is equivalent to about 1650 m^3. Material was removed to a depth of 75 to 100 cm from the water level at the time of dredging.

From this quantity and the results of the sediment sampling analysis, a rough estimate of the WP mass transfer can be made:

Total solids removed:
1650 m^3

Avg. sample (hit) concentration:
6.16 μg/kg (6.16 ppb)

Percent spoils hits:
19%

Possible quantity of contaminated spoils:
$0.19 \times 1650 = 313.5$ m^3

Mass transfer of P_4:
$= 313.5 \times 6.16 \times 10^{-6} = 2$ cm^3
$2 \times 1.82 \times 10^3 = 3600$ mg

To put this number in perspective, it should be considered in terms of lethal doses. Table 7 was constructed using estimates based on Reitsma and Steele (1995) and toxic dose levels were based on Sparling et al. (1995). The quantity of white phosphorus transferred from the Flats to the basin given here is conservative due to the sampling apparatus, as described above.

Table 7. Contaminant removed as a function of lethal doses (1995).

Species	*Lethal dose (mg)*	*Single species mortality*	*Mortality observed (%)*	*Multispecies mortality*
Teal	1.5	2400	26	624
Mallard	4	900	37	333
Pintail	3	1200	37	444
Total		900–2400	100	1401

CONTRACT DEPLOYMENT

In 1996, a local environmental firm was contracted to complete dredging of the 1-ha area begun in 1994. The main objective of CRREL's participation in this phase of the project was to monitor the removal of the white phosphorus-contaminated bottom sediments. Other tasks were to monitor the fate of the contaminated spoils sediments in the retention basin, to measure WP concentrations in the spoils line prior to deposition in the retention basin as well as in the decanted sediment in the basin, and post-remediation sampling within the basin, to determine the efficiency of natural remediation on the sediment within the basin. In addition, CRREL assisted the contractor in equipment deployment, operations instruction, and guidance during the initial phase of operation.

Limited sampling and testing were conducted in the basin and on the spoils entering the basin. Datalogger stations were reinstalled in the basin to monitor such parameters as air and soil tem-

perature, soil moisture, and water level. Before dredging started, two falling water percolation tests were performed in the basin. Soil moisture analyses were also conducted on the basin sediment and liners before dredging resumed. The study of the natural attenuation of planted particles in the basin was continued in a limited scope, and some predredging sediment thicknesses in the basin were measured. After completion of the dredging operations, grab samples were collected from the dredged area and analyzed for white phosphorus. In addition, the area dredged was surveyed, salinity measurements were taken at various locations, organic contents of the basin liner and sediments were measured, two samples of the basin sediment were collected and analyzed for white phosphorus, and an overflight of the Flats was scheduled to obtain photo maps.

difficulties. A number of tests and measurements of retention basin parameters were made in 1996 before and after the conclusion of dredging. The investigations performed on the basin are outlined below.

Basin percolation tests

Before resumption of dredging in 1996, falling water percolation tests were performed on the basin liner to ensure its integrity and suitability for reuse. Two percolation barrels were set in the liner, one in an area of low sedimentation and one in deep sedimentation near the spoils line outfall. These were not rigorous percolation tests (no bentonite sealer was used) and thus only give a rough indication as to the condition of the liner. However, both tests indicated a percolation rate greater than 10^{-4} cm/s, two orders of magnitude

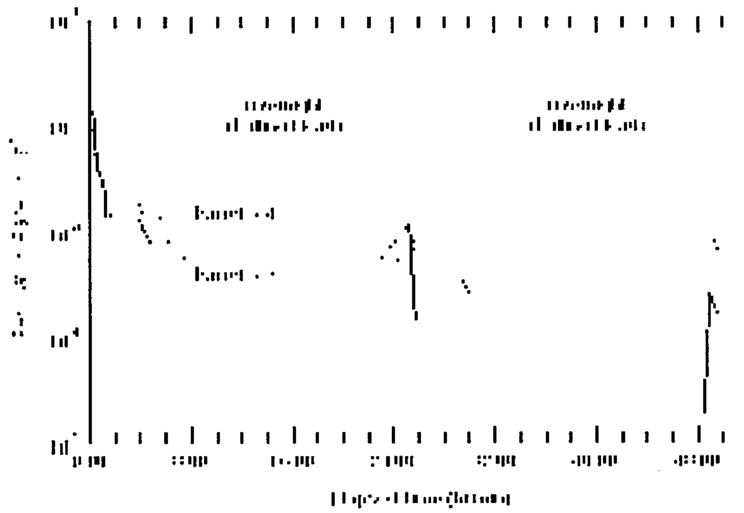


Figure 10. Results of 1996 basin percolation tests.

above the acceptable level of 10^{-6} cm/s (see App. C and Fig. 10). For reference, work done in 1994 by Chamberlain and Walsh (Racine and Cate 1995, Walsh et al. 1996) showed that percolation rates of Flats water through the gravel base below the basin was on the order of 10^{-3} cm/s.

The higher percolation rates are probably caused by a reduction in liner density due to the severe freeze–thaw cycling that occurred over the previous winter, when lack of snow exposed the liner to repeated temperature fluctuations. The lack of funds for improving the liner as well as the proximity of the test results to acceptable levels resulted in the use of the basin in the condition found.

A limited number of sediment moisture content tests were conducted. These are discussed

RESULTS OF 1996 WORK

A number of investigations were carried out to evaluate the feasibility of continuing the dredging operations. In some cases, data are limited and only general conclusions may be drawn. More specific information can be drawn from the in-depth work, such as postdredging sampling and analyses. The following is a breakdown of studies conducted at ERF in 1996 based on general area and specific task. The results are summarized later.

Basin investigations

The retention basin sits on an EPA-designated Solid Waste Management Unit (SWMU), and as such, we felt it critical that we monitor as many relevant parameters as possible to avoid future

under *Attenuation study* later in this report. Unfortunately, time and funding considerations prohibited conducting moisture and density tests of the basin liner. This information would have been very useful in confirming the cause of the sharp increase in hydraulic conductivity of the liner.

Sample sites were surveyed and sediment thicknesses were measured within the basin before the onset of dredging in July. Post-dredging sediment profiles in the basin were surveyed in early October (see *Attenuation study*). Although results of the survey indicate that the basin capacity should be sufficient for at least two more seasons at its current rate of deposition, problems once again occurred during dredging due to long settling times caused by the lack of particulate flocculation due to the low salinity of the supernatant.

Salinity measurements

Salinity measurements were taken on 7 June from several locations around the area to be dredged (Table 8). This was four days after a 31.8-ft flooding tide, a minor flooding event and the first flooding tide since March 21. Although Praudic (1970) states that flocculation increases with salinity levels from 2 through 6 parts per thousand (ppt), our experience has shown that for the extremely fine particles dredged from the Flats, the higher salinity levels are necessary to ensure workable settlement times of less than 12 hours. Work done in 1995 showed that when incomplete settlement of the spoils occurs prior to decantation, total suspended solids of the supernatant are comparable to those found during flooding tides at the Flats (200 to 1600 mg/L vs. 1000 to 3000 mg/L, four samples). Particle size is also very small: Less than 1% is retained by a no. 200 sieve (0.075-mm particle diameter).

Settling times

The low salinities in the area to be dredged did in fact cause problems with decanting the supernatant from the retention basin. The supernatant remained quite cloudy for days after dredging was temporarily halted. Attempts to utilize the geotextile fabric to screen out the suspended solids resulted in minimal decantation due to fabric clogging. This also occurred in the 1995 season. The problem was exacerbated that year as the contractor concentrated dredging efforts during periods of high tides, with their associated influx of low-salinity water.

Using the model for sediment settling times developed by Walsh and Chamberlain (M.R. Walsh et al. 1995), extended settling times are necessary just for the median-sized particles. This model is based on Stoke's Law. The Reynolds number is used to determine if settling is laminar or turbulent. Table 9 shows the results for settling of particles up to the median particle size. Note that the white phosphorus particles take longer to settle than the mineral sediments due to the difference in density.

Table 8. Salinity measurements in dredge area (1996).

Location	*Salinity (ppt NaCl)*	*Temperature (°C)*
Clunie Pad Ramp	3.1	19.8
Clunie Point	2.9	19.1
Canoe Point (N)	4.0	20.1
Off Canoe Point boardwalk	3.4	20.0
Off EOD (EOD pond)	7.0	21.2

Table 9. Settling times for spoils in fresh water.

Retention pond size (ha)	*Particle size (cm)*	*Silt settling velocity (cm/s)*	*WP settling velocity (cm/s)*	*Pond depth (cm)*	*Silt settling time (hr)*	*WP settling time (hr)*	*Dredge cycle (days)**
0.75	0.01	7.0E-1	3.6E-1	40.53	0.02	0.03	0.3
0.75	0.001	7.0E-3	3.6E-3	40.53	1.61	3.14	0.5
0.75	0.0003†	6.3E-4	3.2E-4	40.53	17.89	34.88	1.8

* 8-hr dredging plus retention time. No decanting time included.
† Median particle size (Lawson and Brockett 1993).

An attempt was made to utilize a geotextile filter fabric as a secondary containment and decontamination structure in the basin drop inlet structure. The fine particles quickly clogged the fabric, and repeated scraping of the fabric surface increased flow through the fabric only marginally. The fabric did work well as a secondary backup, holding more than a meter of supernatant back before we slowly lowered the top edge for decantation. However, our attempts to use it to filter out residual particles failed because of the extremely slow settling times due to low salinity. A better use of the filtering fabric may have been in screening out particles in excess of 0.5 mm, half the size of the lethal particles that are sieved by ducks.

Basin monitoring instrumentation

During the initial trip to the Flats in 1996, datalogger instrumentation stations were reinstalled in the retention basin. These stations autonomously monitor sediment moisture and temperature, air temperature, and water levels in the basin. These parameters can then be used in the natural attenuation studies to determine the basin performance and to monitor dredging activities. The dataloggers used for the four sites are the Model CR10 datalogger system manufactured by Campbell Scientific, Inc. (CSI) of Logan, Utah. This system consists of the CR10 Measurement and Control Module, the CR10 Wiring Panel, the PS12 12-volt Power Supply and Charging Regulator, and the SM716 Storage Module. All of the components are housed in a weather-resistant fiberglass-reinforced polyester enclosure that in turn is attached to the central mast of a galvanized steel tripod that consists of three adjustable legs and a central mast with a total height of 3 m.

The most pertinent parameter available from the basin datalogger stations for the retention basin performance is supernatant levels. As mentioned above, the long settling times of the extremely fine suspended particles in the supernatant, combined with the slow decantation rates due to clogging of the geofilter fabric, resulted in long retention times in the basin. This also resulted in high heads. These factors, plus the reduction in the performance of the basin liner, led to increased percolation of supernatant through the liner into the EOD pad below. The drop in surface level of the supernatant, seen in Figure 11, demonstrates this. The 500-mm drop, due to infiltration as well as passage through the geotextile fabric, occurred over the course of 81 hours. This translates to a percolation rate of about 1.6×10^{-4} cm/s. This is a "falling head" rate, and assumes all loss is through the basin liner. Rates near the start and end of this period are 2.1×10^{-4} and 8×10^{-5} cm/s, respectively, averaged over a 3-hour period. At the end of the dredging season, the falling head percolation rate with over 1 m of spoils in the basin was 8.8×10^{-5} cm/s, with start and stop 3-hour rates of 1.6×10^{-4} cm/s and 5.5×10^{-5} cm/s, respectively. Unfortunately, we were unable to monitor the effects on the water table below the EOD pad surface because the EOD pad hydrology monitoring well project was terminated in 1996.

Liner organic content

One final test was performed to determine the basin liner characteristics: an organic carbon content analysis of the peaty-silt liner. Organic content helps determine the ability of the liner to densify

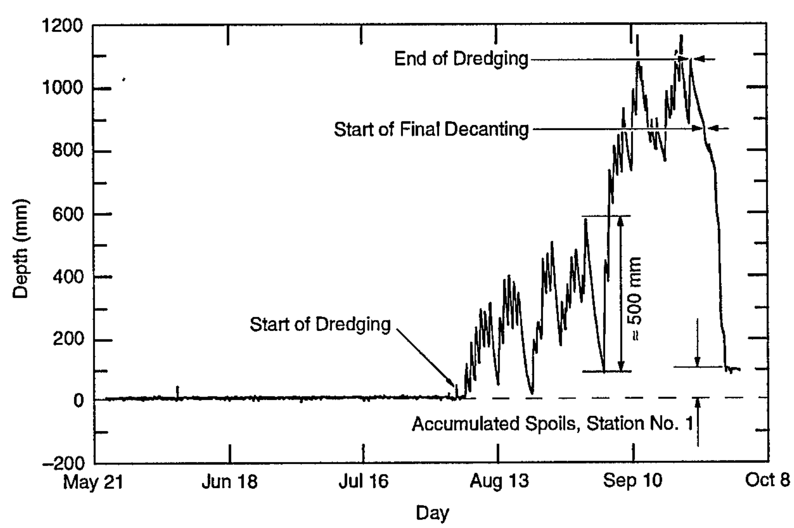


Figure 11. Basin supernatant levels (1996).

and affects the hydraulic conductivity. It also affects the frost susceptibility of the liner: Higher organic content means that more moisture may be held in the material, leading to frost deconsolidation of the liner. Table E2 in Appendix E shows that the organic carbon content of the liner is more than twice that of the sediments commonly found in the Flats. The average of the six samples is 11%, with a median value of 10.9% and standard deviation of ±1.5. This high organic content may well have resulted in deconsolidation of the compacted liner through freeze–thaw cycling and may have contributed to the increase in hydraulic conductivity experienced over the winter of 1995–6.

Dredge monitoring

The actual dredge monitoring segment of the work plan was scaled back to include only occasional visits by one of us (Collins) to the site to determine if the contractor was addressing the areas originally delineated. Although funding for this segment of the work plan was never received, we did continue the work using funds from an unrelated source. In addition, some spoils and supernatant sampling and analyses were conducted during dredging operations. In September, some funding was restored to sample the dredged area for white phosphorus contamination. As funds were limited, a new method of composite sampling, developed by Marianne Walsh of CRREL (M.E. Walsh et al. 1995), was used to maximize the area sampled while minimizing the number of analyses performed. The dredged area was then surveyed, as was the sediment delta in the retention basin. Again, the survey work is discussed later in this report. Finally, Aeromap, Inc., was contracted to collect 1:6,000 aerial photos of the Flats. Aerial photos were needed to document several ongoing projects at ERF, including the pond-draining study, dredging, natural attenuation, and physical systems dynamics.

Spoils line and supernatant sampling and analysis

A small number of samples were collected for analysis during dredging operations at the Flats in 1996. These samples were taken on 13, 21, and 28 August and analyzed at CRREL. Of 12 spoils samples analyzed, three were contaminated with white phosphorus, for a 25% contamination rate. One of five water samples taken from the outflow line was slightly contaminated (< 1 µg/L) (App. C). The small number of samples taken limits the conclusions that can be drawn from the data, although results are similar to those found during the larger sampling program conducted in 1995.

Dredging in 1996 took place in an area known to be more highly contaminated than the areas addressed the previous two years, which may account for the differences in positive results. Results of the spoils line sample analyses indicate that contaminated material continued to be transferred from the Flats to the retention basin.

Post-dredging sampling

Post-dredging sampling occurred in October. Because the area had been swept by an unexploded ordnance detection contractor, bottom surface grab sampling was possible. Sampling occurred over transects oriented perpendicular to the dredge path in all areas except the Clunie Inlet area (Lines 1 and 2, Fig. 12). Sampling in this area and in an area along Clunie Point dredged over the last two seasons was done for reference. Sampling transects were spaced approximately every 10 m. The transects were surveyed after completion of sampling (Fig. 12). An aerial photo of the area depicting the sites is shown in Figure 13.

Sampling data for the dredged area can be found in Appendix C. All samples were sieved composite samples, using a Wildco 190-E20 541-µm sieve bucket (S/N 0594). Subsample points

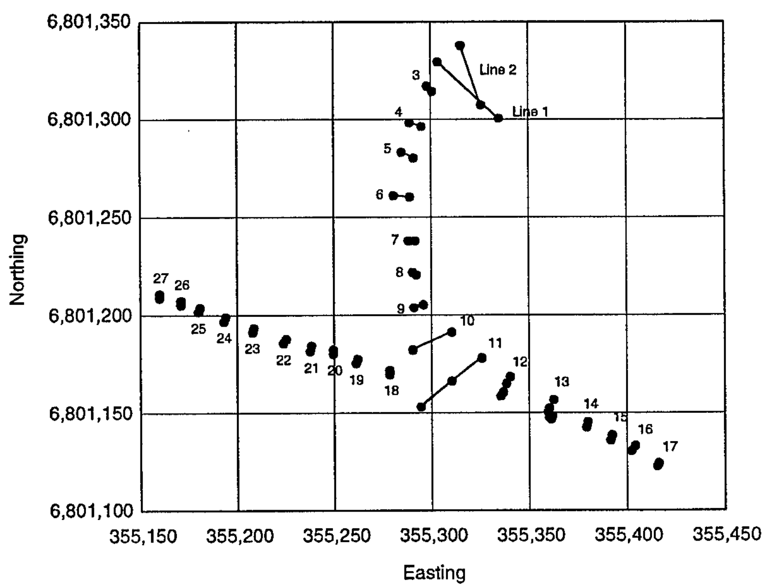


Figure 12. Sampling transects in dredged area.

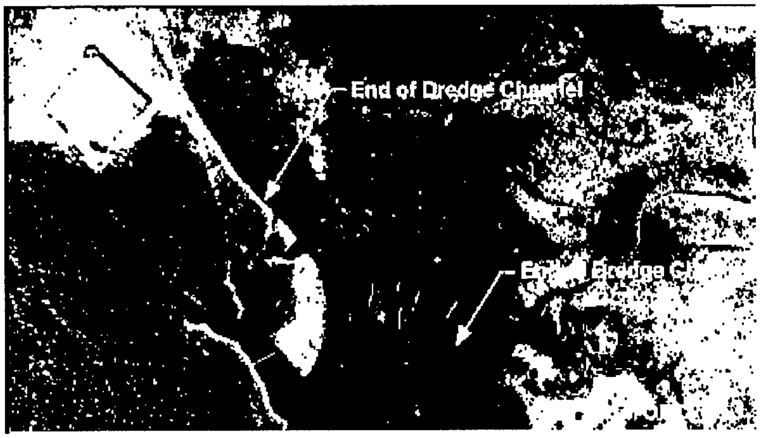


Figure 13. Aerial view of dredged area.

were located every 2 m along each transect, where possible. Subsamples were taken in at least three locations along each transect line except along the channel dredged out to Pond 183 (Fig. 13). Each location was sampled once with a specially designed 250-mL long-handled scoop. Subsamples were deposited in the bucket, which was hung over the edge of the canoe from which sampling was conducted. At the end of the transect, the bucket was agitated and the fines allowed to wash out. Clumps were broken up with a spoon, and the material was resieved. When the material was fully sieved, a 500-mL sample was taken of the remains. On long sample transects, two samples were taken from the bucket for analysis. These are denoted by the "a" and "b" suffixes on the line numbers in the table. The exception is line 11, where two separate samples were taken along the line: one from the east edge to the middle (11a in Table C2) and one from the middle to the west edge (11b in Table C2).

Composite sampling was used for post-dredging sampling for several reasons. The primary reason was that a large area can be sampled quickly and the samples analyzed more economically. Because of the heterogeneous nature of the contaminant, it is difficult to determine if an area is clean. Composite sampling allows better coverage because many points are sampled. Discrete sampling is much more likely to miss possible particulate contamination due to the lower number of samples taken when compared with composite sampling. Discrete sampling is thus more likely to result in a false negative for a given number of analyzed samples.

Analysis of the dredged area sampling indicates that a small area is still slightly contaminated. The likely source of the contamination is material slumped from the edges of the dredge channel. Two out of 30 samples were contaminated, for a contamination rate of less than 7%. This compares with discrete sample contamination rates of between 50% and 80% and composite sample contamination rates approaching 100% for areas known to be contaminated, based on past investigations at the Flats (Racine 1995).

The concentration and number of contaminated samples for the compositing technique cannot be compared directly with data obtained from discrete sampling because the composite samples are preconcentrated by sieving. This will overstate the presence of WP in comparison to a series of discrete samples. For instance, in this study, over 150 total discrete subsamples went into the 28 composite samples analyzed. The two composite samples testing positive each contained at least 10 subsamples. The small number of detections and the wide variation in the concentration (two orders of magnitude) makes any additional statistical analysis of the data difficult, if not meaningless. It should be used for comparison with other areas of known contamination which, as stated above, normally have detection rates approaching 100% using the sieved composite method.

In addition to the spoils line and dredged area sampling, two sediment samples were analyzed from the retention basin. These samples were obtained near the spoils outfall pad where sedimentation is thickest and drying time is longest (see *Attenuation study*). Both 500-mL samples, taken from material from the same 20-cm depth, were contaminated. Results are shown in Table C2 as "Basin."

Survey methods

Detailed surveying was conducted to determine horizontal coordinates and elevations of sample locations and boundaries in the dredged area dur-

ing October 1996. Surveying was done using a Leitz SET4B electronic total station and a triple reflective prism mounted on a 1.45-m-tall prism rod. For the dredge area survey, we used two benchmarks (BMs), Canoe Point BM and Clunie BM, along the shore near the area dredged that had been previously surveyed. For the retention basin we used two benchmarks (Berm and Crane) located on the EOD pad. Universal Transverse Mercator (UTM) horizontal coordinates and the elevation were known for each of the benchmarks.

For the dredged area survey, a 20-cm-diam. flat plate was attached to the tip of the prism rod. This provided a uniform bearing surface for the rod tip, keeping it from sinking down into the pond bottom sediment. The plate was located at the flat bottom of the dredged area rather than attempting to locate the tip halfway up the slumped edge of the dredged channel. A more accurate reading of the dredge depth was obtained in this manner, and a horizontal offset factor was added to the area surveyed to compensate for the displacement of the tip.

Dredge area survey

Both the perimeter of the area dredged in 1996 and spot measurements of dredge depths within the dredged area were surveyed. A map of the dredged area is shown in Figure 14. The total area dredged in 1996 was approximately 2915 m^2, or about 0.72 acres. The average dredged depths along the sample transect lines and at additional locations within the dredged area are given in Appendix C. The average depth for the area dredged in 1996 was 63 cm (25 in.). Certain areas, such the channel from Canoe Point Pond out to Pond 183 were much shallower, averaging 45 cm (18 in.). Only a few areas within the center of the dredged area came close to the target depth of 90 cm (36 in.). Minimum depth for breaking the contaminant pathway to feeding mallards, the largest of the dabbling ducks, is 40 cm (Low et al. 1970).

Attenuation study

A scaled-down version of the natural attenuation project and the ongoing contaminant attenuation study being conducted in the retention basin were carried out in 1996. These studies are extremely important in evaluating the efficacy of various remediation studies being conducted at ERF. Due to restrictions on working in the Flats, we concentrated on the parameters affecting the sublimation of white phosphorus in the basin sediments.

Soil moistures

In early June, a series of soil moisture measurements were made in the sediments of the previous years' dredging activities. Soil cores 2 cm in diameter were taken down to liner depth at 10 different locations in the basin. Four of these locations corresponded to areas where plugs containing WP particles had been planted the previous fall when the basin attenuation study was initialized. The other six locations follow the tapering sediment delta between the corner of the fencing around the north spoils splash pad and Instrument Station 1, both locations of particle plugs (Fig. 15). The other two plug locations are at Instrumentation Station 3 and between the berm and splash pad, adjacent to the spoils inlet pipe.

The data indicate that the sediment in most locations and depths was still nearly saturated

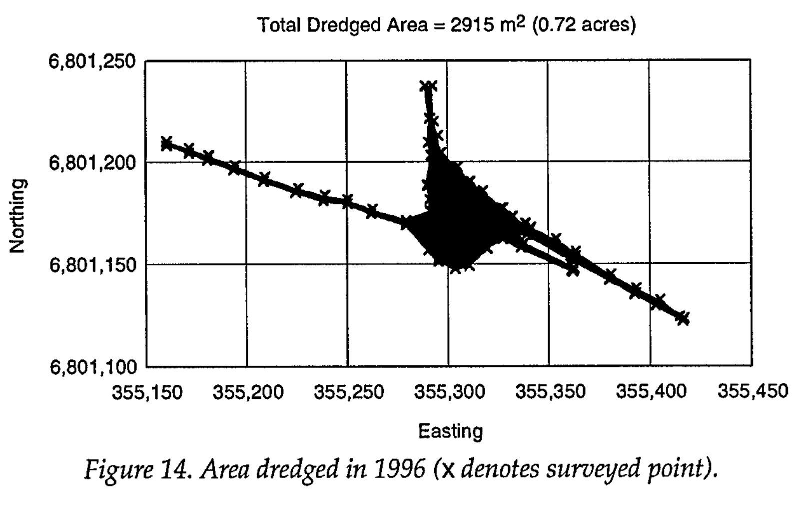


Figure 14. Area dredged in 1996 (x denotes surveyed point).

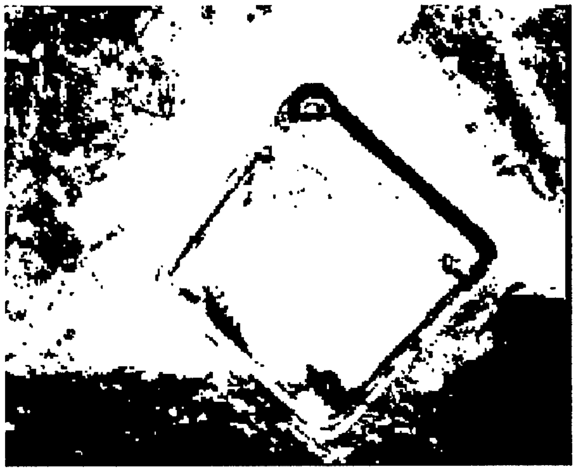


Figure 15. Retention basin.

after the winter season, with moisture contents of up to 105% (Table E1). The exceptions are those sample points near Station 1 where sediment thickness is least. Here, moisture contents were in the 10% to 20% range (dry weight basis). The sediment in these areas is also mostly mineral, with very little organic material evident. This results in quicker drying times. For sublimation to occur, moisture content levels must be below approximately 45% (dry weight basis) (M.E. Walsh 1995).

Organic contents

As organic content of the sediments directly affects the drying rate, two samples were obtained from the basin, one near the spoils splash pad and one from the basin liner. These samples were subdivided and analyzed at CRREL for organics . The samples were first dried in an oven at 105°C until the moisture was driven off. Portions of the sample were sieved with a no. 30 sieve prior to analysis. Samples were analyzed in a Leco CR-12 furnace using the methods outlined in Merry and Spouncer (1988). Analyses included both the sieved and unsieved portions of the original sample. Replicates of both the sieved and unsieved analyses were run. The weights of two samples were measured to verify the ranges of the carbon contents. Data and results are found in Appendix E.

The average for the five samples used in these analyses is 4.3%, the median 4.4%, and the standard deviation ±0.3. The organic contents of the sieved and unsieved basin sediment samples are in the same range as those found by Bouwkamp (in Racine and Cate 1995). In Bouwkamp, 36 of 42 samples analyzed had organic carbon contents in the 2.2–6.8% range. Organic content has a great impact on drying times of the sediments and sorption of colloidal white phosphorus. No organic content analyses were performed on sediments farther from the spoils outfall. It is postulated that the values will reflect those of the sediment removed at the greater dredged depths and should be quite low.

WP particle plug attenuation

On 28 September 1995, after draining the retention basin, manufactured particles of white phosphorus (M.E. Walsh et al. 1995) were planted in the dredge sediments at four locations in the basin to monitor attenuation of a known quantity of white phosphorus in the basin sediments over time. A single manufactured WP particle, approximately 2 mm diameter, was inserted in a plug of sediment contained within a nylon mesh bag. Six plugs were planted at each of the four locations. Using other data such as sediment moisture content, organic content, and temperature, the efficacy of using the basin for natural remediation of white-phosphorus-contaminated sediments can be determined.

In May 1996, before dredging resumed, three plugs from each of the four locations were pulled by Marianne Walsh for analysis at CRREL. At that time, the sediments were still partially frozen and temperatures were averaging below 7°C, going below 0°C at night. Very little of the warm drying conditions necessary for the initiation of the sublimation process was seen between the end of September 1995 and the end of May 1996. Table 10, the results of the analyses on the plugs, reflects this.

These results are very similar to the results obtained in studies conducted in intermittent pond areas of ERF (M.E. Walsh et al. 1995). As the sediments approach desaturation, individual particles

Table 10. Analysis results for P_4-spiked plugs in basin.

Site	*Rep*	*WP mass found (μg)**	*% remaining*
Station 1	a	not detectable	0.00
	b	7.80	0.14
	c	not detectable	0.00
Station 3	a	4400.0	80.59
	b	0.14	0.0026
	c	0.17	0.0031
Mid inflow pipe	a	4690.0	85.90
	b	3308.0	60.60
	c	629.0	11.50
Fence corner	a	32.0	0.59
	b	0.2†	0.0037
	c	4402.0	80.60

* Samples analyzed by M.E. Walsh at CRREL using SPME and GC.

† Sample bag broke on extraction from basin.

start to sublimate as void pathways through the soil structure become available. Variations in the availability of pathways through the soil account for the wide variability in the amount of WP mass remaining. Another set of plugs will be analyzed in September of 1997 to indicate the results of a full year of drying. Preliminary results indicate that the contaminant has naturally attenuated and is no longer present.

Basin contamination

Prior to dredging in 1996, a series of samples was collected from the retention basin for analysis for white phosphorus. The results would be an important indicator for estimating how well the natural attenuation of the contaminant was progressing. Sample points corresponded with the locations chosen for the soil moisture samples (see Table E1). As can be seen from Table 11, no white phosphorus was detected at any of the sample points. This does not prove that the contaminant has completely disappeared from the basin, only that the contaminant is not widespread and that, in areas where sampled, it has either disappeared through natural attenuation or was never deposited there. More intensive sampling of the basin will be necessary to obtain more reliable results.

Table 11. Results of limited basin sampling (1996).

Site ID	*WP mass found (μg)**
5 m	Not detectable
10 m	Not detectable
15 m	Not detectable
20 m	Not detectable
25 m	Not detectable
30 m	Not detectable
Station 1	Not detectable
Station 3	Not detectable
Fence corner	Not detectable
Inflow pipe	Not detectable

* Samples analyzed using SPME.

Within the retention basin, the locations of the planted WP particle plugs and sediment moisture sample points were surveyed (see App. E). A profile of the sediment delta was surveyed to determine the distribution and depths of sediment built up in the retention basin (Table E5) for the 1996 season's dredging effort. Although survey data indicate the capacity of the basin has not been fully utilized, removal of the sediment will be necessary to compact the liner before the structure can be reused.

SUMMARY

The retention basin hydraulic conductivity has increased to the point where it will not be useable another season without recompaction, and it probably should not have been used during the 1996 season. The probable cause of deterioration is freeze–thaw cycling over the winter, caused by the retention of water in the highly organic liner material. Low salinities continue to plague flocculation and settlement of the suspended solids and negate the usefulness of the filter fabric in the drop inlet structure. The low salinities result in a lack of particulate flocculation, which in turn leads to prolonged settling times, with the result that continuous dredging is not practical if TSS is to be below levels found in the Flats during flooding tides. Basin sedimentation rates should allow for at least two more dredging seasons before it will be necessary to remove the sediments.

Using the instrumentation located on the four stations in the basin to monitor basin use is a good way to record contractor performance at the Flats. It is also useful in determining rough percolation rates and thus basin performance. Soil temperature and moisture sensors should be useful if the attenuation study is continued. No analysis on this has been done to date.

Spoils line sample analyses indicate that contaminant rates are comparable to those found in previous years. Presence of contaminant in the basin from current year dredge spoils confirms transfer of contaminant to the basin. Some low-level amounts of WP contaminant are still being rereleased from the decantation of supernatant from the basin into the Flats. However, this is most probably colloidal, not particulate, in form and should quickly be sorbed onto the vegetation in the area.

Composite sampling techniques made it much easier to sample the area dredged in 1996. They may be magnifying the problem of residual contamination, however, by consolidating the contaminant from a large number of samples along a sampling line into a single sample, thereby overemphasizing isolated hits and exaggerating concentrations. Post-dredge sampling indicates that some contaminant is still being left behind after dredging, albeit at significantly lower occurrences than before dredging (<7% hits vs. ≈100 %). Causes of the contamination may be as follows:

- Contamination may be coming from slumped banks on the edge of the dredged area. This is the most likely cause.

- Contamination may be occurring in areas that were not dredged to a full depth of 90 cm (36 in.), leaving contaminated sediments behind. Some post-dredging sedimentation and recontamination may have occurred. This is highly unlikely.

Results cannot be compared with discrete sampling method results because of the compositing of subsamples.

The area dredged in 1996 was about 0.3 ha (0.7 acre). The average depth is 63 cm (25 in.), a depth sufficient to break the contamination pathway for mallards, the largest of the dabbling ducks. The area dredged in 1995 was about 0.15 ha, bringing the total area dredged since the inception of the dredging study to about 0.45 ha, or 1 acre.

No dead ducks or swans were observed in or near dredged areas. The length of the channel dredged out to C Pond in 1996 will not be sufficient for the blast and drain approach. It also does not increase the connectivity between the Clunie Pond area and Pond 183 in Area C, a highly contaminated area that is a candidate for further dredging or pumping.

Results of the abbreviated attenuation study for dredging are limited. Overwinter conditions are not conducive to drying of sediments. Sediment sample soil moisture contents averaged around 77% in June in areas where thickness exceeded 18 cm. Some attenuation of contaminant will occur even under these less-than-ideal conditions. About 20% of the WP particles in planted plugs disappeared overwinter in moist areas, and all the WP was gone at the one dry area.

The organic content of dredged sediments reflects those typical of the Flats in area adjacent to the spoils line (≈ 4.5%). Sediments farther from the deposition delta appear to be inorganic. The organic content of the basin sediments highly influences attenuation of contaminant. Results of limited basin sampling prior to the 1996 dredging indicate that most of the contaminant is gone from the sediments.

RECOMMENDATIONS

The following recommendations are made based on work done from 1993 through 1996. They are listed to correspond to the order of the subject matter in this report and are not in order of importance or urgency.

1. Further optimization of the dredge system will facilitate the dredging process. Refinement of the anchoring system, use of a wireless remote control system, additional extended cutter tines, and relocation of the auger drive should all be considered.
2. Retention basin hydraulic conductivity has increased to the point where it will be necessary to recompact the liner before reuse. Use of a geotextile fabric as a liner may be necessary for long-term stability due to the susceptibility of the liner to freeze–thaw deconsolidation.
3. The capacity of the basin is sufficient for at least two more seasons. It is not necessary from a capacity viewpoint to remove the sediments at this time, although they may have to be removed for effective recompaction of the liner.
4. The use of a coagulant such as aluminum sulfate (alum) or a polymer will facilitate the flocculation and settlement of suspended solids in the basin and should reduce the reintroduction of trace amounts of colloidal white phosphorus into ERF. Alum is effective for pH values of 5.5 to 8.0 (Corbit 1990), which covers the range of conditions found in ERF (Racine et al. 1993). Polymers have been used effectively to treat runoff at mine sites in Alaska such as the Usibeli Coal Mine at Healy.
5. Basin investigations should be continued to ensure the viability of the system. The basin hydraulic conductivity should be checked yearly to ensure integrity.
6. Closer monitoring of the dredging operation by the Contract On-site Representative (COR) may be necessary to ensure that the parameters of the contract are being met and progress is being reported correctly. We found the dredged area to be half what the contractor claimed anAd the dredged depth was not to specifications.
7. The attenuation study should be continued to monitor the efficiency of the natural attenuation process in the basin. Without this information, too many assumptions will have to be made in determining the treatment and remediation of the contaminated sediment. The basin is a safe, representative area in which some controlled attenuation studies may be conducted.
8. The absence of waterfowl mortality in and adjacent to the dredged areas, which were

shown to be highly contaminated prior to dredging, indicates that dredging contaminated areas is contributing to the reduction of mortality at the Flats.

9. Aerial photo overflights should continue, to document yearly changes in the topography of the Flats as well as to monitor dredged areas.
10. Work should be restarted on the water table monitoring wells to determine the influence of basin infiltration, if any, and tides on the EOD pad water table.
11. Dredging should continue to be considered as a remediation strategy at the Flats. A rigorous economic analysis of the feasibility of dredging will need to be conducted before further dredge work is contracted. Other remediation methods, such as pond pumping, may prove to be more economical as well as less disruptive to the long-term viability of the Flats.

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APPENDIX A: ANALYSIS OF DREDGE PUMP OPTIONS

Static head calculations were made to determine the theoretical head at full flow. Friction factors were derived from empirical data.* The following parameters were used:

- Flow—113.5 L/s
- Friction factor—25-cm-diam. polypipe: 1.69 m/100 m
- Friction factor—20-cm-diam. rubber hose: 3.7 m/100 m
- Height of top of berm from water level: 6.52 m
- Drop from berm to spoils line outlet: 0.81 m

Total head for the system:

- Static head: 6.52 – 0.81 = 5.71 m
- Friction head, polypipe (335 m): 335 × 1.69/100 = 5.7 m
- Friction head, hose (76 m): 76 × 3.7/100 = 2.81

Total head will be the sum of all three components above, or:

$$h = h_s + \Sigma h_f = 5.71 + 5.70 + 2.81 = 14.22 \text{ m.} \quad \text{(A1)}$$

The friction head for the PE pipe was also calculated using the Hazen–Williams formula to verify the empirical data:

$$h_f = 10.44\,(L)(Q)^{1.85}/[(C)^{1.85}\,(D)^{4.8655}] \quad \text{(A2)}$$

where L = length of pipe in feet (1000 ft)
Q = flow through the pipe (1800 gpm)
C = Hazen–Williams constant ≈1.40 for PE)
D = pipe inside diameter in inches (≈10 in.).

Substituting the values and constants above for PE pipe into eq A2 and converting, we get

$$h_f = 1.61 \text{ m}/100 \text{ m} \quad \text{(A3)}$$

thus validating the value used in eq 1. Design pump flow is actually 106.3 L/s, thus the total head (h_T) we should see at the dredge should be approximately

$$h_T = h_s + (V_1/V_2)^2\,(\Sigma h_f) \quad \text{(A4)}$$

$$h_T = 5.71 + (106.3/113.5)^2\,(5.7 + 2.81)$$

$$h_T = 13.2 \text{ m} \quad \text{(A5)}$$

Using 998 kg/m^3 as the density of the pumped water, the actual power head is

$$h_T = P_{out}/\rho \quad \text{(A6)}$$

$$h_T = (103 \times 10^3)\,(10.2 \times 10^{-2})/998$$

$$h_T = 10.5 \text{ m.} \quad \text{(A7)}$$

The total head is about 30% less than what the system output should be if the equipment were operating properly. A call to the equipment manufacturer resulted in the discovery that the pump trim and pressure relief settings were not correct. The system was set up with a 356-mm (14-in.) impeller operating at 1250 rpm. It was designed to run with a 300-mm (12-in.) trim operating at an 1800-rpm impeller speed (Fig. A1).

Given this situation, there were three options available. The first was to leave the impeller as is and increase the hydraulic pressure to run the pump at a sufficient speed to attain the flow rates in the specifications. As can be seen below (Fig. A2), that speed is 1470 rpm. Note that the power requirements are the same due to increased pump efficiency. The second option was to trim the impeller to 330 mm (13 in.) and increase the pressure to attain the correct flow. The third option was to trim the impeller to 300 mm (12 in.) and increase the impeller speed to make the pump operate as originally planned. The first option was the quickest method of obtaining the desired result, so that option was favored. However, before a decision could be made, other factors, such as computed head, available power, and available suction needed to be examined. A shortfall in any of these three parameters would dictate the consideration of an alternative strategy.

A system analysis was performed using the pump affinity laws. For the system as delivered we have the following parameters:

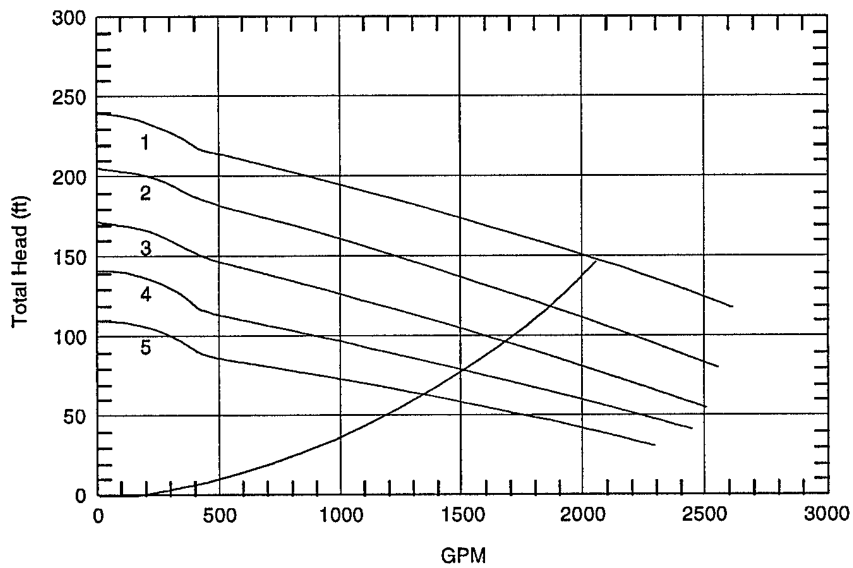
Trim: 356 mm (14 in.)
Max. shaft speed: 1280 rpm
Max. outlet pressure: 110 kPa @ 11.25 m head (16 psi @ 36.9 ft head)

The first calculations are for a 12-in. (300-mm) trim. Adjusting for trim using the head relationship

$$\frac{h_2}{h_1} = \left(\frac{d_2}{d_1}\right)^2 \quad \text{(A8)}$$

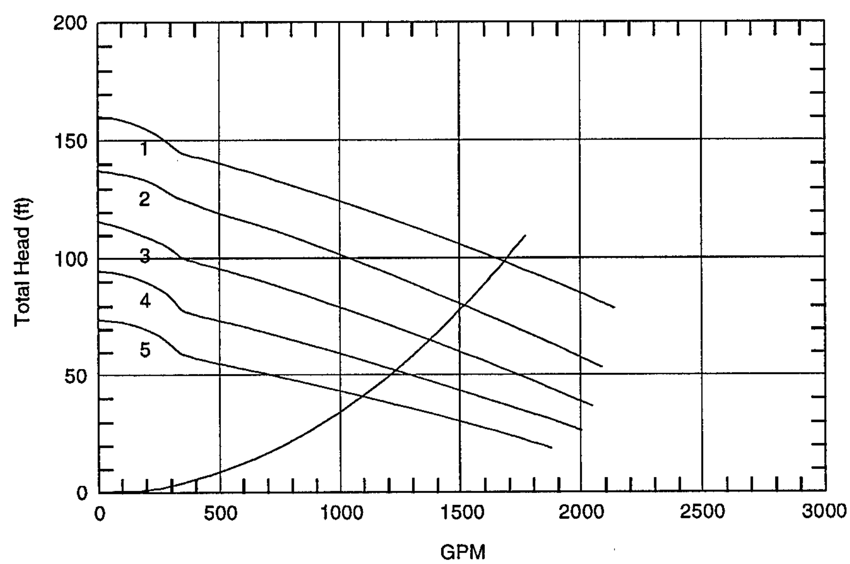
where h_1 = current outlet head
h_2 = projected outlet head
d_1 = original impeller diameter
d_2 = impeller diameter of interest,

* Telephone conversation regarding pump and pipe performance, R. O'Brien, Cornell Pump Co., 1995.



	Design point	Curve	Trim	Max. hp @ 1.0 SG
Flow (U.S. gpm)	1685	1	14.00	53.21
Head (ft)	100	2	13.00	37.46
Speed (rpm)	1470	3	12.00	27.82
Trim (in.)	14	4	11.00	20.82
Horsepower (hp)	50.5	5	10.00	15.12
Efficiency (%)	83.7			
Static head (ft)	0.0			

Figure A1. Pump curves for 1800-rpm impeller. (Adapted from Cornell 1995.)



	Design point	Curve	Trim	Max. hp @ 1.0 SG
Flow (U.S. gpm)	1685	1	14.00	97.70
Head (ft)	100	2	13.00	68.78
Speed (rpm)	1800	3	12.00	51.08
Trim (in.)	12	4	11.00	38.23
Horsepower (hp)	50.5	5	10.00	27.75
Efficiency (%)	81.8			
Static head (ft)	0.0			

Figure A2. Pump curves for 1470-rpm impeller. (Adapted from Cornell 1995.)

$$\frac{h_2}{110} = \left(\frac{30.4}{35.6}\right)^2$$

$\therefore h_2 = 80.2$ kPa @ 1280 rpm (11.6 psi).

Adjusting for speed using the head/speed relationship,

$$\frac{h_2}{h_1} = \left(\frac{n_2}{n_1}\right)^2 \tag{A9}$$

where n_1 is the original impeller rotational rate, and n_2 is the rate of interest,

$$\frac{h_2}{80.2} = \left(\frac{1800}{1280}\right)^2$$

$\therefore h_2 = 159$ kPa (16.4-m head)
@ 1800 rpm (23.3 psi @ 53.8 ft).

The next series of calculations are for a 330-mm (13-in.) trim. The equations used are the same, giving us

$$\frac{h_2}{110} = \left(\frac{33.0}{35.6}\right)^2 \quad \text{(Ref. A8)}$$

$h_2 = 94.5$ kPa @ 1280 rpm (13.8 psi) (Ref. A9)

$\therefore h_2 = 187$ kPa (19.2-m head)
@ 1800 rpm (27.3 psi/62.9 ft).

Finally, for the 35.6-cm trim, we need adjust for impeller speed only:

$$\frac{h_2}{94.5} = \left(\frac{1800}{1280}\right)^2 \quad \text{(Ref. A9)}$$

$h_2 = 218$ kPa (22.3-m head)
@ 1800 rpm (31.6 psi/73 ft).

Referring to Figure A1, we should be capable of around 45 m (150 ft) of head. Lack of line resistance is the probable cause of this differential. Referring back to Figure A2, the outlet head is calculated for an impeller speed of 1500 rpm:

$$\frac{h_2}{110} = \left(\frac{1500}{1280}\right)^2 \quad \text{(Ref. A9)}$$

$h_2 = 151$ kPa (15.6-m head)
@ 1500 rpm (22 psi /51 ft).

If the 35.6-cm impeller option is chosen, the outlet pressure should be about 151 kPa (22 psi) for the same configuration as the original. This allows much greater flexibility in operations due to the greater available pressure range for dredging.

The next factor to be examined is the power requirement. For this, the classic fluid power equation is used:

$$P = (0.9751)pQ \tag{A10}$$

where P = required power (kW)
p = system pressure (MPa)
Q = fluid flow rate (L/s).

The impeller drive motor requires about 0.065 liters per revolution. Table A1 illustrates the various power requirements for different system configurations.

Table A1. Slurry pump power requirements.

Impeller speed (rmp)	*Pressure (MPa)*	*Flow (L/s)*	*Power (kW)*
1280	24.1	1.4	32.9
1280	31.0	1.4	42.3
1500	24.1	1.6	38.6
1800	24.1	1.9	46.3
1800	31.0	1.9	59.5

A total of 74.5 kW of power is available at the electric motor driving the hydraulic pumps. Two other systems are driven off the auxiliary hydraulic pump. The auger motor requires about 8.9 kW at full power, 80% efficiency, and the traverse drive requires about 0.4 kW at the same conditions. Using these numbers, a total of 65.2 kW is available to drive the slurry pump. Using an efficiency factor of around 80%, the greatest power utilization comes at an impeller speed of just below 1500 rpm with line pressure at 31 MPa (4500 psi). These are the conditions for which the 35.6-cm impeller works best.

Finally, the net positive suction head available (NPSHA) needs to be examined to ensure cavitation does not occur. The equation normally used is

$$\text{NPSHA} = h_a + h_s - h_{fs} - h_{vp} \tag{A11}$$

where h_a = atmospheric head
h_s = static suction head
h_{fs} = friction loss in the suction line
h_{vp} = vapor pressure head.

Atmospheric pressure is taken as 10.3 m. For static suction head, the intake for the pump is 0.48 m below water level. Friction head loss is calculated

on the basis of pipe diameter, fluid speed, and roughness:

Pipe diameter: 0.154 m (6-in. Schedule 40 pipe)

Pipe cross-sectional area: 0.02 m^2

$$v = \text{fluid speed} = Q/A \tag{A12}$$

Q = 0.106 m^3/s (system requirement)

$\therefore v = 0.106/0.02 = 5.7$ m/s.

Entrance loss is calculated on the basis of fluid velocity and an entrance loss coefficient, K_e. In this case, K_e is 0.5, based on a flush, square-edged entrance (Lindeburg 1984, p. 3–24).

$$h_e = K_e\left(\frac{v^2}{2g_c}\right) \tag{A13}$$

(opening is 1.56 times larger than hose).

$h_e \approx 0.3$ m.

Equivalent lengths of the various components are taken from standard tables:

Short 90° (eye inlet):	2.75 m
Intake hose (6 in.):	2.44 m
Entrance loss (see above):	0.3 m.

Total equivalent length is therefore 5.5 m. To calculate the suction friction loss, the Darcy equation is used:

$$h_f = \frac{f(L)(v)^2}{2Dg_c}. \tag{A14}$$

Using cold, clear water,

$\nu = 1.11$ cS ($\approx$ 16°C).

Plugging into the formula for the Reynolds number,

$$N_{Re} = \frac{D_e v}{\nu} \tag{A15}$$

results in a Reynolds number of

$$N_{Re} = \frac{(0.15)(5.7)}{1.11\times10^{-6}}$$

$$N_{Re} = 7.8\times10^5$$

which is in the turbulent region. To determine the Darcy friction factor f, the relative roughness ratio, ε/D, must be estimated. Using 0.15 m for the hose diameter and a specific roughness $\varepsilon = 1\times10^{-5}$ (Lindeburg 1984),

$\varepsilon/D = 6.7\times10^{-5}$.

Using the relative roughness and Reynolds number to find the Darcy friction factor from a Moody friction factor chart, we find that

$f \approx 0.014$.

Plugging these values into eq A14 results in a head of 0.85 m. Finally, the vapor pressure head at 16°C is 0.18 m. Filling in the values derived for eq A11, we get

NPSHA = 10.33 + 0.49 – 0.85 – 0.18

NPSHA = 9.8 m (32.2 ft).

Using a set of pump curves from the manufacturer (not shown), a net positive suction head required of approximately 4.6 m is necessary at 106 L/s (15 ft @ 1685 gpm). For higher flow rates, which occur with lower outlet line resistances (shorter lines), the NPSHA drops quickly. At 142 L/s, the NPSHA becomes 7.3 m, and at 190 L/s, which we were approaching with only 76 m of hose attached to the dredge, we are at or slightly above the NPSHR. However, for our operations, the 356-mm (14-in.) impeller operating near 1500 rpm should work well.

With the slurry pump hydraulic system pressure relief valve set to 33 MPa (4800 psi), the pump tests were rerun. The data, as shown in Table A2, are as expected from the calculations above.

Table A2. Final pump performance test results.

Control setting (%)	*Slurry pump Outlet (kPa)*	*Slurry pump Hyd. (MPa)*	*Outlet flow (visual)*
100	108.9	33	Full pipe
95	108.9	33	Full pipe
90	108.9	33	Full pipe
85	108.9	33	Full pipe
80	108.9	33	Full pipe
75	108.9	33	Full pipe
70	108.9	33	Full pipe
65	104.8	31	Full pipe
60	95.1	27	Near full pipe
55	85.5	23	Near full pipe
50	75.8	20	Near full pipe
45	64.1	6	[a] 7/8 pipe
40	54.5	12	[a] 3/4 pipe
35	47.6	10	[a] 5/8 pipe
30	42.7	6.2	1/3 to 1/2 pipe
25	37.9	4.8	Trickle

APPENDIX B: DATA FOR FALLING HEAD PERCOLATION TESTS IN BASIN

The following data were obtained from falling water percolation tests conducted in June of 1996 to determine the state of the retention basin liner. The barrels were sealed with local material: no bentonite was used. For reference, work done in 1994 by Chamberlain and Walsh (Racine and Cate 1995, Walsh et al. 1996) showed that percolation rates of Flats water through the gravel base below the basin were on the order of 10^{-3} cm/sec.

Table B1. Basin percolation barrel tests data—1996.

	*Barrel S-3**				*Barrel S-4**			
Date	*Time*	*Elapsed time (min)*	*Head drop (cm)*	*Percolation rate (cm/s)*	*Time*	*Elapsed time (min)*	*Head drop (cm)*	*Percolation rate (cm/s)*
10 June	9:30	0	0.0	—	9:38	0	0.0	—
	9:45	15	10.0	1.39 E-02	9:53	15	7.0	9.00 E-03
	10:00	15	4.0	4.81 E-03	10:08	15	3.5	4.17 E-03
	10:15	15	2.8	3.28 E-03	10:23	15	2.8	3.28 E-03
	10:30	15	2.5	2.91 E-03	10:38	15	2.6	3.04 E-03
	10:45	15	1.2	1.36 E-03	10:53	15	2.3	2.67 E-03
	11:00	15	1.2	1.36 E-03	11:08	15	2.0	2.31 E-03
	11:35	35	3.3	1.68 E-03	11:38	30	3.7	2.21 E-03
	13:15	100	7.0	1.35 E-03	13:18	100	9.3	1.90 E-03
	13:45	30	1.8	1.03 E-03	13:48	30	2.3	1.34 E-03
	14:15	30	1.4	7.99 E-04	14:18	30	2.6	1.52 E-03
	14:45	30	1.4	7.99 E-04	14:48	30	2.1	1.21 E-03
	15:23	38	2.0	9.11 E-04	15:25	37	3.1	1.48 E-03
	15:50	27	1.2	7.58 E-04	15:52	27	2.0	1.28 E-03
	16:20	30	1.2	6.82 E-04	16:23	31	2.2	1.23 E-03
	16:56	36	1.2	5.68 E-04	16:58	35	2.1	1.04 E-03
11 June	8:30	934	27.0	—	8:30	34,052	27.0	—
	10:38	128	7.5	1.14 E-03	10:40	130	2.6	3.50 E-04
	11:12	34	0.3	1.48 E-04	11:15	35	1.9	9.38 E-04
	14:51	219	4.5	3.75 E-04	14:50	215	10.7	1.06 E-03
	15:30	39	0.6	2.59 E-04	15:33	43	2.2	8.89 E-04
12 June	9:51	1101	20.2	5.64 E-04	9:49	34,216	27	—
	10:22	31	0.5	2.71 E-04	10:19	30	1.8	1.03 E-03
	10:52	30	0.3	1.68 E-04	10:49	30	1.2	6.82 E-04
	11:25	33	0.3	1.52 E-04	11:22	33	1.2	6.20 E-04

* Barrels 39.3 cm diam with 27 cm water when full.
Material thickness: Barrel S-3: 34 cm
Barrel S-4: 13.5 cm

APPENDIX C: RESULTS OF ANALYSIS OF SAMPLES FOR WHITE PHOSPHORUS

Table C1. Results of spoils line sampling during 1996 dredging activities.

Sample no.	*Component*	*Sample site*	*Mass/vol. (g/mL)*	*Concentration WP*
Subsampled on 30 Aug 96*				
813.01	Sediment	Spoils line	40.73	—
	Water		25.00	—
813.02	Sediment	Spoils line	40.26	—
	Water		25.00	—
813.03	Sediment	Spoils line	40.42	0.008 μg/g
	Water		25.00	0.0801 μg/L
813.04	Sediment	Spoils line	40.71	0.0241 μg/g
	Water		25.00	3.996 μg/L
813.05	Sediment	Spoils line	40.75	7.394 μg/g
	Water		25.00	0.546 μg/L
813.06	Sediment	Spoils line	40.32	—
	Water		25.00	—
Subsampled on 30 Aug 96 and 3 Sept 96				
821.01	Water	Outflow pipe	25.00	0.115 μg/L
821.02	Sediment	Spoils line	40.39	—
	Water		25.00	—
821.03	Sediment	Spoils line	40.67	—
	Water		25.00	—
821.04	Sediment	Spoils line	40.92	—
	Water		25.00	—
821.05	Sediment	Spoils line	40.25	—
	Water		25.00	—
821.06	Sediment	Spoils line	13.41	—
	Water		25.00	—
Subsampled on 3 Sept 96				
828.01	Water	Outflow pipe	25.00	—
828.02	Water	Outflow pipe	25.00	—
828.03	Water	Basin, inside	25.00	—
828.04	Sediment	Spoils line	40.31	—
	Water		25.00	—
828.05	Water	Outflow pipe	25.00	—

* Analyzed and re-analyzed with SPME on 3 Sept 96.
SPME positives extracted in isooctane overnight and analyzed with a GC.

Table C2. Post-dredging sample data.

Line	*Site*	*WP mass found (μg)*	*Wet sample mass (g)*	*Concentration WP (μg/g)**
1a	Clunie Pond	not detectable	534	—
1b	Clunie Pond	not detectable	521	—
2a	Clunie Pond	not detectable	502	—
2b	Clunie Pond	not detectable	478	—
3	Clunie Channel	not detectable	513	—
4	Clunie Channel	not detectable	573	—
5	Clunie Channel	not detectable	526	—
6	Clunie Channel	not detectable	504	—
7	Clunie Channel	not detectable	527	—
8	Clunie Channel	not detectable	505	—
9	Clunie Channel	not detectable	487	—
10a†	Canoe Pt. Pond	40.4	531	0.076
10b†	Canoe Pt. Pond	151.0	538	0.281
11a	Canoe Pt. Pond	not detectable	542	—
11b	Canoe Pt. Pond	2055.	540	3.800
12	Canoe Pt. Pond	not detectable	653	—
13	Canoe Pt. Pond	not detectable	545	—
14	Canoe Pt. Pond	not detectable	522	—
15	Channel to EOD	not detectable	520	—
16	Channel to EOD	not detectable	525	—
17	Channel to EOD	not detectable	569	—
18	Channel to EOD	not detectable	539	—
19	Channel to Pond 183	not detectable	553	—
20	Channel to Pond 183	not detectable	448	—
21	Channel to Pond 183	not detectable	405	—
22	Channel to Pond 183	not detectable	503	—
23	Channel to Pond 183	not detectable	495	—
24	Channel to Pond 183	not detectable	516	—
25	Channel to Pond 183	not detectable	330	—
26	Channel to Pond 183	not detectable	182	—
27	Channel to Pond 183	not detectable	191	—
—	Basin 1	2.82	619	0.005
—	Basin 2	162	607	0.267

* Samples analyzed at CRREL using SPME by M.E. Walsh, November 1996. Hits reanalyzed using GC. Concentrations are from composite samples. Do not compare with discrete sample results.
† Duplicate samples.

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APPENDIX D: SURVEY DATA FOR DREDGED AREA AND SAMPLE POINTS

The data in Table D1 were obtained from 30 September to 2 October 1996 as part of the sampling and evaluation tasks for the dredge project. Water depths are referenced to the water surface at the time of surveying. Flooding tides (10.1 m max.) occurred from 25 September to 1 October. Surveying was done using a Leitz SET4B electronic total station and a triple reflective prism mounted on a 1.45-m-tall prism rod.

Table D2 contains survey data for nonperipheral dredged areas. These points were used to weight the average depth calculations for reporting purposes. They are more representative of the overall depth of dredging as they are measured away from the edge slumping.

Table D1. Dredged depths at survey point locations.

Transect	Location	Avg. depth* (m)	Avg. depth* (in.)	Starting coordinate Easting	Starting coordinate Northing	Ending coordinate Easting	Ending coordinate Northing
Line 1	Clunie Inlet	0.77	30	355,335.18	6,801,299.28	355,303.83	6,801,328.47
Line 2	Clunie Inlet	0.78	31	355,326.43	6,801,306.59	355,316.30	6,801,337.13
Line 3	Clunie Channel	0.75	30	355,301.42	6,801,313.17	355,298.91	6,801,316.19
Line 4	Clunie Channel	0.70	28	355,295.52	6,801,294.76	355,289.53	6,801,297.67
Line 5	Clunie Channel	0.74	29	355,291.54	6,801,279.73	355,285.73	6,801,281.78
Line 6	Clunie Channel	0.71	28	355,289.42	6,801,259.21	355,281.19	6,801,259.50
Line 7	Clunie Channel	0.47	19	355,292.41	6,801,237.20	355,288.83	6,801,236.90
Line 8	Clunie Channel	0.52	20	355,293.19	6,801,219.50	355,291.25	6,801,220.85
Line 9	Canoe Pt. Pond	0.60	24	355,296.45	6,801,203.88	355,291.38	6,801,203.23
Line 10	Canoe Pt. Pond	0.59	23	355,311.11	6,801,190.62	355,291.15	6,801,181.23
Line 11	Canoe Pt. Pond	0.73	29	355,326.26	6,801,177.17	355,295.25	6,801,152.00
Line 12	Canoe Pt. Pond	0.72	28	355,340.86	6,801,167.50	355,335.83	6,801,157.38
Line 13	Canoe Pt. Pond	0.73	29	355,363.18	6,801,155.62	355,361.12	6,801,146.36
Line 14	Ch. to EOD	0.75	30	355,380.38	6,801,144.34	355,379.52	6,801,141.43
Line 15	Ch. to EOD	0.75	30	355,393.18	6,801,137.71	355,392.33	6,801,134.46
Line 16	Ch. to EOD	0.71	28	355,404.67	6,801,131.94	355,403.01	6,801,128.82
Line 17	Ch. to EOD	0.64	25	355,416.88	6,801,122.81	355,415.83	6,801,121.40
Line 18	Ch. to Pond 183	0.52	20	355,279.21	6,801,170.52	355,278.87	6,801,168.46
Line 19	Ch. to Pond 183	0.60	24	355,262.69	6,801,176.53	355,261.66	6,801,174.64
Line 20	Ch. to Pond 183	0.37	15	355,249.83	6,801,181.32	355,250.25	6,801,178.99
Line 21	Ch. to Pond 183	0.41	16	355,238.83	6,801,183.37	355,238.27	6,801,180.45
Line 22	Ch. to Pond 183	0.38	15	355,225.38	6,801,186.64	355,224.33	6,801,184.92
Line 23	Ch. to Pond 183	0.36	14	355,209.22	6,801,192.47	355,208.47	6,801,190.57
Line 24	Ch. to Pond 183	0.42	17	355,194.39	6,801,197.80	355,193.80	6,801,195.94
Line 25	Ch. to Pond 183	0.41	16	355,181.21	6,801,202.92	355,180.76	6,801,200.84
Line 26	Ch. to Pond 183	0.50	20	355,171.80	6,801,206.30	355,171.26	6,801,204.29
Line 27	Ch. to Pond 183	0.61	24	355,160.24	6,801,207.34	355,160.70	6,801,209.40

* Based on a water surface elevation of 4.83 m at the time of survey on 2 Oct 96. Previous flooding high tide night of 30 September.

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Table D2. Dredged depths at other locations (additional points within center of dredged area).

Transect	*Location*	*Water depth** (m)	*Water depth** (in.)	*UTM coordinates* Easting	*UTM coordinates* Northing
Point 30	Canoe Pt. Pond center	0.83	33	355,292.92	6,801,210.87
Point 31	Canoe Pt. Pond center	0.71	28	355,293.93	6,801,203.77
Point 32	Canoe Pt. Pond center	0.79	31	355,301.31	6,801,187.94
Point 33	Canoe Pt. Pond center	0.75	30	355,307.35	6,801,177.26
Point 34	Canoe Pt. Pond center	0.69	27	355,302.72	6,801,168.55
Point 35	Canoe Pt. Pond center	0.67	27	355,305.93	6,801,156.76
Point 36	Center, Ch to Pond 183 entrance	0.54	21	355,278.88	6,801,169.64
Point 37	Pond center	0.71	28	355,300.93	6,801,160.16
Point 38	Pond center	0.84	33	355,320.62	6,801,170.14
Point 41	Center of E channel (Line 12)	0.76	30	355,340.28	6,801,165.94
Point 42	Center of E channel (Line 13)	0.78	31	355,362.99	6,801,153.42
Point 43	Channel center	0.79	31	355,393.03	6,801,135.73
Point 44	Channel center	0.66	26	355,414.57	6,801,123.65
	Average depth (all areas):	0.64	25.2		
	Average depth (1996)†:	0.63	24.8		
	Average depth (Ch. to Pond 183):	0.45	17.7		

* Based on a water surface elevation of 4.83 m at the time of survey on 2 Oct 96. Previous flooding high tide night of 30 September.

† 1996 season began at transect 7.

APPENDIX E: BASIN SEDIMENT CHARACTERIZATION DATA AND ANALYSIS

The tables in this appendix contain data and analyses from work done to characterize the dredge spoils in the retention basin. Table E1 contains moisture content data for the spoils pumped into the basin during the 1995 dredging season. These data are indicative of the overall effectiveness of the basin as a remediation tool for contaminated sediments removed from the Flats. Although reduction of moisture content was only measured over the winter season, significant drying of the less organic material found farther from the outfall is a positive outcome. The more organic (and thicker) deposits nearer the inlet pipe outfall will require a more extensive drying period before the required reduction to approximately 45% moisture content can be achieved.

Table E2 contains data and analyses of the organic carbon content of the sediments in the basin from the 1996 season as well as the basin liner. Organic content of the sediments is indicative of the material dredged and is directly related to the amount of time required for drying to occur. The organic content of the liner is important for the sorption of colloidal white phosphorous, which may percolate through the liner, as well as the susceptibility of the liner to freeze–thaw deconsolidation.

The overall average organic carbon content of the sediment samples is 5.4%, the median 5.0%, and the standard deviation ±2.2. Eliminating the outliers brings the average to 4.6%, the median to 4.8%, and the standard deviation down to ±0.98. This is comparable to previous analyses of sediments from the Flats.

Tables E3 and E4 contain survey data for the test locations in the retention basin. Table E3 con-

Table E1. Moisture contents of basin sediment samples (June 1996).

Location	Sample number	Depth (cm)	Soil + Tare Wet (g)	Soil + Tare Dry (g)	Water wt. (g)	Soil wt. (g)	Soil moisture content† (%)
Inlet	P-00:10	0 to 10	49.27	30.37	18.90	21.23	89.02
Pipe	P-10:20	10 to 20	41.75	26.02	15.73	16.56	94.99
	P-20:30	20 to 30	39.31	23.99	15.32	14.51	105.58
	P-30:40	30 to 40	46.73	29.66	17.07	20.47	83.39
	P-40:45	40 to 45	28.90	20.40	8.50	11.34	74.96
Fence	F-00:10	0 to 10	51.33	33.39	17.94	24.31	73.80
Corner	F-10:20	10 to 20	44.08	28.03	16.05	18.58	86.38
	F-20:30	20 to 30	46.02	28.61	17.41	19.51	89.24
	F-30:37	30 to 37	33.75	22.99	10.76	13.83	77.80
5 m out *	5-00:10	0 to 10	50.24	33.37	16.87	24.01	70.26
	5-10:20	10 to 20	38.68	25.72	12.96	16.31	79.46
	5-20:30	20 to 30	48.94	31.02	17.92	21.90	81.83
	5-30:33	30 to 33	21.31	16.43	4.88	7.13	68.44
10 m out *	10-00:10	0 to 10	41.73	28.65	13.08	19.45	67.25
	10-10:20	10 to 20	41.50	26.67	14.83	17.21	86.17
	10-20:24	20 to 24	34.04	24.60	9.44	15.54	60.75
15 m out *	15-00:10	0 to 10	45.59	30.06	15.53	20.67	75.13
	15-10:20	10 to 20	42.93	28.59	14.34	19.27	74.42
	15-20:28	20 to 28	41.23	29.59	11.64	20.14	57.80
20 m out *	20-00:10	0 to 10	44.47	31.48	12.99	22.20	58.51
	20-10:18	10 to 18	40.42	28.41	12.01	18.95	63.38
25 m out *	25-00:10	0 to 10	48.44	36.59	11.85	27.23	43.52
	25-10:13	10 to 13	23.54	19.08	4.46	9.74	45.79
30 m out *	30-00:10	0 to 10	32.30	28.44	3.86	19.14	20.17
Station 1	S1-00:05	0 to 5	25.14	23.67	1.47	14.25	10.32
Station 3	S3-00:10	0 to 10	54.28	38.16	16.12	28.70	56.17
	S3-10:16	10 to 13	27.65	20.44	7.21	10.99	65.61

* Distance from fence corner on splash pad to Station 1.

† As a percentage of dry weight.

Table E2. Organic carbon content analyses.

Run no.	Source	Condition	Carbon content (%)	Target content (%)	Calibration error (%)
1	Standard	—	71.5	71.1	0.6
2	Liner	Sieved	9.8	—	—
3	Liner	Sieved	11.9	—	—
4	Liner	Sieved	12.3	—	—
5	Standard	—	10.7	12	10.8
6	Liner	Unsieved	9.3	—	—
7	Liner	Unsieved	9.8	—	—
8	Basin	Sieved	4.2	—	—
9	Standard	—	12.2	12	1.7
10	Basin	Sieved	4.5	—	—
11	Basin	Sieved	4.4	—	—
12	Liner	Sieved	12.8	—	—
13	Basin	Unsieved	4.5	—	—
14	Basin	Unsieved	3.9	—	—

tains the survey data for the particle plugs also used in the attenuation study, the results of which can be found in Table 10. Related data for Table E4 can be found in Table E1 above and under *Soil moisture* in the *Attenuation study* section under *Results of 1996 work.*

Data in Table E5 can be used to estimate both the amount of material removed from the Flats as well as how much more capacity remains in the basin. Station 1 is located in the center of the basin, and the depth of sediment there indicates that at least two more seasons and possibly up to four seasons' additional use is possible from the existing structure without removal of existing sediments. The condition of the liner, however, will preclude further use of the basin until the liner can be recompacted and percolation rates return to acceptable levels. (See Table B1 and Figure 10.)

Table E3. White phosphorus particle plug locations.

Location	Easting	Northing	Elevation (m)
Fence corner	355,616.14	6,801,126.35	9.88
Pipe site	355,608.66	6,801,130.58	9.96
Sta. 3 sample site	355,601.07	6,801,109.77	9.58
Sta. 1 sample site	355,629.66	6,801,090.50	9.51

Table E4. Sediment moisture sample points.

Location	Easting	Northing	Elevation (m)
Sample pt: 30 m out	355,627.13	6,801,098.26	9.56
Sample pt: 25 m out	355,625.66	6,801,102.62	9.53
Sample pt: 20 m out	355,623.55	6,801,107.75	9.62
Sample pt: 15 m out	355,621.54	6,801,112.84	9.61
Sample pt: 10 m out	355,619.85	6,801,117.68	9.68
Sample pt: 5 m out	355,617.85	6,801,122.46	9.81
Fence corner	355,616.14	6,801,126.35	9.88

Surveyed on 6 June 1996.

Table E5. 1996 pre- and post-dredging sedimentation delta depths within the retention basin.

Location	Depth (cm) June 96	Depth (cm) Oct 96
Inlet pipe near plugs	45	89
Fence corner near plugs	37	78
5 m out	33	59
10 m out	24	55
15 m out	28	61
20 m out	18	45
25 m out	13	38
30 m out	10	29
Inst. station 1 (37.8 m out)	4	16
40 m out	0	12
50 m out	0	11
Inst. station 3	16	44

Surveyed on 6 June and 2 October 96.

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13. ABSTRACT (*Maximum 200 words*)

The Eagle River Flats impact area is a Ft. Richardson Superfund site. It is a salt marsh that is contaminated with white phosphorus (WP), and remediation of sediments in permanently ponded areas may require dredging. A remotely piloted dredging system was designed, constructed, and deployed at the Flats as part of the overall site remediation feasibility study. Experience gained over two years of engineering study and contract operation indicates that, although feasible and effective, this alternative is slow, difficult, and very expensive.

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